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Reconfiguration of polar-cap plasma in the magnetic midnight sector

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Abstract. Radio tomography and the EISCAT and SuperDARN radars have been used to identify long-lived, high-altitude, cold plasma in the antisunward convective flow across the polar cap. The projection of the feature to later times suggests that it was reconfigured in the Harang discontinuity to form an enhancement that was elongated in longitude in the sunward return flow of the high-latitude convection pattern. Comparison with a tomographic image at a later time supports the interpretation of a polar patch being reconfigured into a boundary blob. There is also evidence for a second plasma enhancement equatorward of the reconfigured blob, likely to have been produced by in situ precipitation. The observations indicate that the two mechanisms proposed in the literature for the production of boundary blobs are operating simultaneously to form two distinct density features separated slightly in latitude.

Keywords. Ionosphere (Ionosphere-magnetosphere interactions; Plasma convection; Polar ionosphere)

1 Introduction

The polar ionosphere is highly complex containing structures in electron density with a wide range of spatial scale sizes. Of relevance to the current study are density enhancements on horizontal scales of ∼100 s to 1000 s km in the F-region, known as polar patches. These patches were studied first using ionospheric sounders and airglow emissions (Buchau et al., 1983; Weber et al., 1984), but they have since been investigated by a variety of experimental techniques, including radio scintillation (Buchau et al., 1985), incoherent scatter radar (Pedersen et al., 1998), HF radar (Ogawa et al., 1998) and radio tomography (Walker et al., 1999). However, comparisons of features observed by different techniques are not always straight-forward, with different techniques using different criteria to define a patch. A comprehensive review of the structures and associated phenomena has been given by Crowley (1996).

Polar patches are found when the interplanetary magnetic field (IMF) B_z component is negative (McEwen and Harris, 1996). They drift anti-sunward in the cross-polar flow at speeds of typically between 300 and 1000 m s^{-1}. The patches have been observed in both winter and summer at sunspot maximum and minimum (Buchau and Reinisch, 1991) and in geomagnetically conjugate regions (Rodger et al., 1994a). Complete understanding of the mechanisms responsible for the increased density is still open, with both soft-particle precipitation (Weber et al., 1984) and photoionisation at sub-polar latitudes (Buchau et al., 1985) being cited. Experimental evidence is increasingly supportive of the latter idea, suggesting that dayside photoionisation from lower latitudes is entrained into the polar convection pattern and is subsequently structured into discrete patches. Patch density levels comparable to those at dayside sub-auroral latitudes were reported by Buchau et al. (1985), whilst the observations of Pryse et al. (2004) indicated that the enhanced density could have originated in the postnoon sector, near the equatorward edge of the high-latitude convection pattern. The observations of Valladares et al. (1994) suggested that the plasma convected from sub-auroral latitudes into the polar cap in a tongue-of-ionisation (TOI), and supportive evidence for a latitudinally-extended feature near magnetic noon was presented by Sims et al. (2005). The break-up of the TOI into patches has been attributed to many processes, including temporal changes in the plasma convection pattern due to variations in the IMF B_y component (Sojka et al., 1993), the expansion of the convection throat of the polar cap to lower latitudes (Anderson et al., 1988) and increased plasma loss in flow channel events (Rodger et al., 1994b), but the balance of the contributions of the different mechanisms remains an open question. Modelling studies of the

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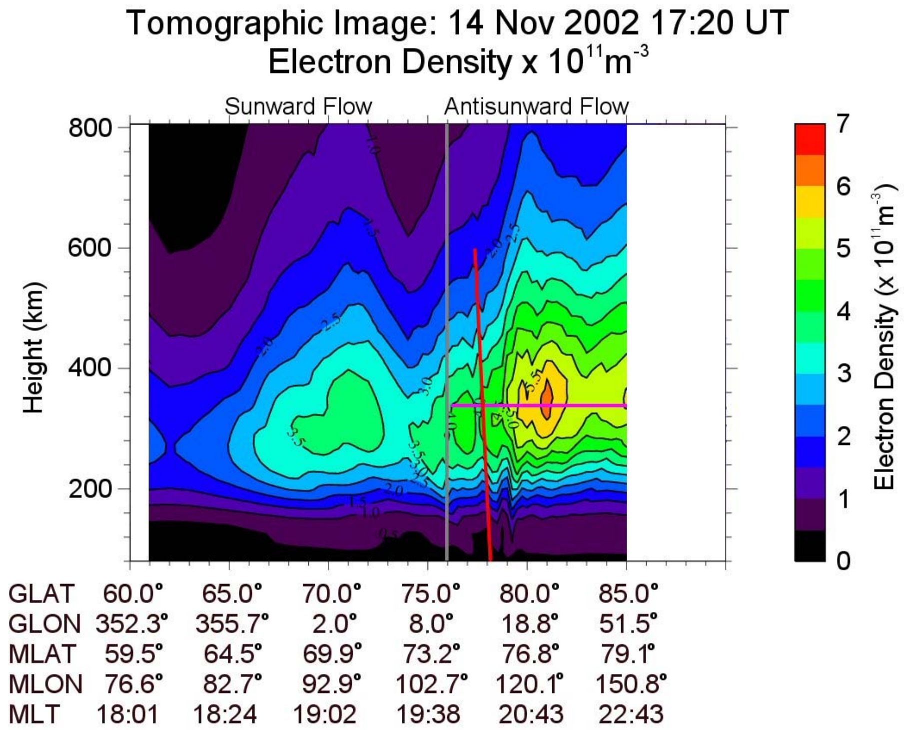

Fig. 1. Tomography image for a southbound satellite pass crossing the latitude of 75° N at 17:20 UT on 14 November 2002. The pink horizontal line indicates the observed latitudinal extent of enhanced densities at an altitude of 350 km. The line extends from the equatorward edge of the enhancement in the antisunward flow, defined by the 4×10^{11} m^{-3} electron density contour, to the poleward extreme of the field-of-view. The vertical grey line shows the location of the flow reversal boundary between sunward and antisunward flow identified by the SuperDARN electric potential map at 17:16 UT. The red line near 78° N indicates the observing direction of the EISCAT Svalbard Radar 42-m dish.

polar ionosphere have shown that the TOI can be modulated by IMF B_y, the season and UT effects (Sojka et al., 1993; 1994) as it is drawn antisunward from the dayside across the polar cap. A subsequent study discussed the dependency of the UT modulation on the observing location, by considering three locations in different longitude sectors (Bowline at al., 1996). This indicated that the feature was expected to be prominent at Ny-Ålesund in the European sector in the evening under conditions of B_y negative.

An earlier modelling investigation by Robinson et al. (1985) suggested that a polar density enhancement could be drawn out of the polar cap on the nightside through the Harang discontinuity. Further restructuring of the feature in the zonal convective flow might result in a longitudinally extended, but latitudinally-confined boundary blob in the return sunward convection flow of the auroral region. Experimental observations of the boundary blobs in the evening auroral ionosphere have been reported by Rino et al. (1983) and Jones et al. (1997). It was suggested that the feature in the former study was produced by localised precipitation, while the blob in the latter study was observed by the EISCAT radar to be produced in situ by ongoing soft-particle precipitation. The mechanism of formation of such blobs thus remains open to debate. This current paper presents a case study in support of formation by re-configuration of a polar patch, as suggested by the earlier modelling study. However, a second field-aligned enhancement was also observed in the region of return, sunward flow that was consistent with production by soft-particle precipitation. The understanding of the occurrence and formation of the boundary blobs is of relevance to the mitigation of propagation effects on radio systems, where steep density gradients at the poleward edge of the mid-latitude trough can present particular problems (Pryse et al., 2006).

2 Experimental facilities

2.1 Radio tomography

The radio tomography experiment operated by the University of Wales Aberystwyth comprises a chain of receivers at four locations in northern Scandinavia, separated in latitude but aligned essentially in longitude: Ny-Ålesund (78.9° N, 12.0° E; 76.0° MLAT, 112.3° MLON), Longyearbyen (78.2° N, 15.7° E; 75.1° MLAT, 113.0° MLON), Bjørnøya

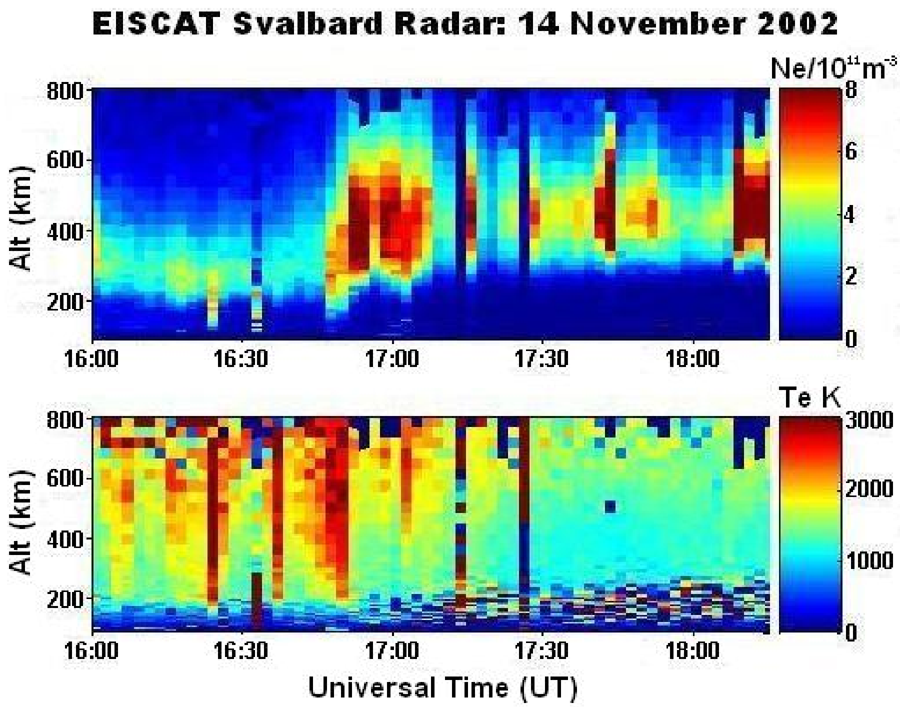

Fig. 2. Electron densities (top panel) and temperatures (bottom panel) measured by the EISCAT Svalbard Radar 42-m dish observing along the geomagnetic field.

(74.5° N ,19.0° E; 71.3° MLAT, 108.8° MLON) and Tromsø (69.8° N, 19.0° E; 66.1° MLAT, 103.4° MLON). Phase coherent signals from the polar orbiting satellites of the Navy Ionospheric Monitoring System (NIMS) are received at each site to measure total electron content along the satellite-to-receiver ray paths. The collective observations during a satellite pass from a large number of intersecting ray-paths are inverted in a tomographic algorithm to yield the spatial distribution of electron density in a height-versus-latitude plane through the ionosphere (Pryse, 2003 and references therein).

2.2 EISCAT Svalbard radar

The international European Incoherent Scatter radar (EISCAT) facility comprises instrumentation on mainland northern Scandinavia and at Longyearbyen on Svalbard. Of particular interest to the current work are measurements of ionospheric electron density and temperature made by the static 42-m dish of the EISCAT Svalbard radar (ESR) (78.2° N, 16.1° E 75.0° MLAT, 113.1° MLON,) which observes along the local geomagnetic field line in the F-region.

2.3 Super dual auroral radar network

The Super Dual Auroral Radar Network, SuperDARN, (Greenwald et al., 1995) consists of nine coherent scatter radars at high latitudes in the Northern Hemisphere and seven in the Southern Hemisphere. These radars measure the line-of-sight velocity of the F-region convection flows. The observations can be inverted using the spherical harmonic fitting technique described by Ruohoniemi and Baker (1998) to produce global maps of the ionospheric convection pattern and the high-latitude electric potential, which are used in the present study.

3 Experimental observations

3.1 Radio tomography image 17:20 UT, 14 November 2002

The tomographic image for a southward satellite pass that crossed the geographic latitude of 75° N at 17:20 UT on 14 November 2002 is shown in Fig. 1. The image reveals an ionosphere structured in latitude with a density enhancement in the northern field-of-view. The enhancement extends from about 74° MLAT to beyond the poleward extremity of the field-of-view and has a density maximum of greater than 6×10^{11} m^{-3} near 77.5° MLAT. Its latitudinal extent is highlighted by the horizontal pink line at an altitude near 350 km, which extends poleward from the 4×10^{11} m^{-3} contour on the equator-most side of the feature. A second, smaller enhancement is also to be seen at a similar altitude, centred near 70° MLAT with density levels reaching some 3.5×10^{11} m^{-3}. The vertical grey line down the image indicates the location

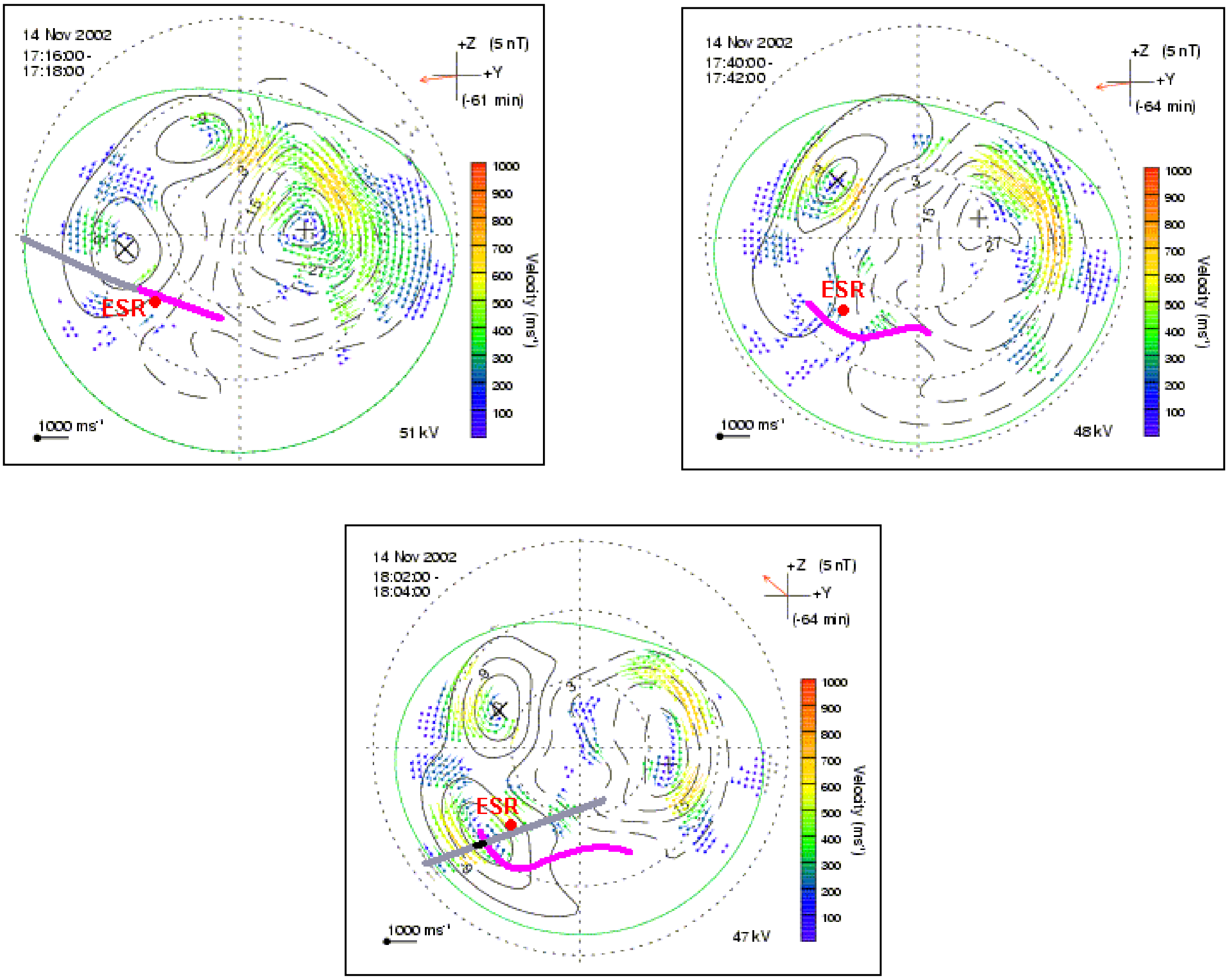

Fig. 3. SuperDARN electric potential maps for 17:16 UT (first panel), 17:40 UT (second panel) and 18:02 UT (third panel) on a magnetic latitude versus MLT polar plot. The latitudinal extent of the polar patch as observed at 17:20 UT is mapped onto the first plot and is shown by the pink portion of the satellite trajectory mapped to 350 km. The anticipated locations of the enhancement following projection through the electric potential patterns are shown by the pink curves in the subsequent panels. The electron density enhancement observed in the tomography image at 18:02 UT lies in the return flow and is indicated in the bottom panel by the short dark blue line on the trajectory for this pass.

of the flow-reversal boundary between the cross-polar anti-sunward flow and the return flow of the dusk convection cell, identified from the SuperDARN measurements (Sect. 3.3).

3.2 EISCAT Svalbard Radar 16:00 UT–18:15 UT, 14 November 2002

The electron densities and temperatures measured by the 42-m dish of the ESR radar between 16:00 UT and 18:15 UT are shown in the two panels of Fig. 2. The fixed observing direction of the dish (Azimuth: –179.0°, Elevation: 81.6°) is aligned along the magnetic field. Two clear regimes are apparent in the panels. In the earlier part of the data record before about 16:45 UT, the F-region layer peak is below 300 km and the sporadically increased electron temperatures are indicative of ongoing soft-particle precipitation. At later times the maximum height of the F-region peak is closer to 400 km and electron temperatures are consistently low. It can also be noted that significant temporal structure can be seen, with changes in peak density by at least a factor of two taking place on a time scale of minutes. At about 17:20 UT the radar beam was close to the plane of the tomography image. Its pointing direction is indicated by the red line near 78° N in Fig. 1. The density at the peak was measured between 3 and

$4\times10^{11}\,\mathrm{m}^{-3}$, in broad agreement with the tomographic observation at the same location. The high altitude of the layer peak and the low electron temperatures at this time indicate that the density enhancement in the tomography image comprised long-lived cold plasma, created well before the observation and convected into the field of view. It can be noted that the altitude of the layer peak, marginally above 400 km, is higher than in the tomographic image. However, it must be recalled that, in addition to small differences in the co-location of the measurements, the radio tomographic technique is limited in its ability to reconstruct precisely the vertical distribution of the electron density (Pryse, 2003), though this restricted ability to determine the exact height of the peak does not detract from the validity of the present study.

3.3 SuperDARN electric potential maps 17:16 UT–18:04 UT, 14 November 2002

Measurements in the solar wind upstream of the Earth indicated that the IMF was exerting a reasonably constant influence on the polar ionosphere at the time of interest. Observations by the ACE spacecraft, with appropriate adjustment of just over 1 h for the delay between measurement and the ionospheric flow-response, showed that the clock angle was dominated by an IMF B_y component with values between –7 nT and –4 nT, whilst the B_z component fluctuated between +4 nT and –4 nT. The electric potential maps from the SuperDARN radars, examined at 2-min intervals, were correspondingly reasonably stable with each showing a dawn cell that was larger and more rounded than the dusk cell, in keeping with the negative B_y component. The pattern for the interval starting at 17:16 UT is shown in the first panel of Fig. 3, in terms of magnetic latitude and MLT with local noon at the top. The time corresponds to the time of observation of the main enhancement in Fig. 1, just before the 75° N crossing of the NIMS satellite at 17:20 UT. Also shown in the panels of Fig. 3 are the horizontal velocity vectors derived from the ionospheric backscatter measured by the radars, which have been used to shape the electric potential patterns. In the ionospheric F-region, the $\boldsymbol{E}\times\boldsymbol{B}$ drift transports plasma along the equipotential contours, so that at the time of interest there was a general antisunward flow across the polar cap, slightly displaced towards dusk, consistent with the patterns of Cowley et al. (1991). The trajectory of the 17:20 UT tomography satellite pass mapped to 350 km is shown in the first panel by the grey and pink line that extends from about 60° MLAT to 80° MLAT in the evening sector. The pink northern-most part of the trajectory corresponds to the latitudinal extent of the polar density enhancement marked in Fig. 1. It can be seen that the enhancement lies exactly in the antisunward plasma flow between the two cells. Also shown on the panel is the intersection of the ESR radar at the corresponding time.

Plots similar to those of Fig. 3 were used to project the development of the plasma feature indicated on the first panel forward in time, by estimating the strength and direction of the electric field from the potential gradients. The field was initially determined at regular intervals of 1° geographic latitude along the line through the feature in the first panel, then each of these points was projected forward in location with the velocity of the $\boldsymbol{E}\times\boldsymbol{B}$ drift through a time interval of 2 min. The process was repeated on the same points using potential patterns at 2-min separation until 18:02 UT. The centre panel of Fig. 3 shows an intermediate projection of the polar patch for the 2-min interval starting at 17:40 UT, with the third panel showing the final projected location at 18:02 UT. It can be seen that in the latter plot the equatorward edge of the patch lies in the sunward return flow of the dusk cell, while the poleward extreme extends towards the return flow of the dawn cell, with the overall feature now being drawn out in longitude along the auroral region.

3.4 Radio tomographic image 18:02 UT, 14 November 2002

The radio tomographic image for a later southward satellite pass at 18:02 UT is shown in Fig. 4. Of particular interest is the density enhancement between 68° MLAT and 70° MLAT, as defined by the $3\times10^{11}\,\mathrm{m}^{-3}$ contour. Its latitudinal cross-section is indicated by the horizontal dark blue line. The trajectory of the satellite pass mapped to an altitude of 350 km is shown by the grey line in the third panel of the electric potential patterns of Fig. 3. The short dark blue segment on the trajectory corresponds to the latitudinal cross-section through the density enhancement identified in the tomography image, and is seen to lie in the sunward return flow of the dusk cell almost coincident with the projection of the polar patch.

4 Discussion

Experimental observations have been presented of a large-scale density enhancement on the nightside of the antisunward plasma flow across the polar cap ionosphere. The high altitude and cold electron temperatures suggest that the plasma had been produced upstream at an earlier time. In the absence of a local solar EUV or impact ionisation source, the plasma decays at the lower altitudes where recombination rates are higher. A horizontal cross-section through the enhancement was projected forward in time using the SuperDARN electric potential maps. A later tomographic image showed good agreement of a density enhancement with the projected location of the convecting plasma. The results suggest that the plasma at the lower latitudes of the polar patch had been carried through the Harang discontinuity and elongated in the return sunward flow of the dusk cell to form a boundary blob in the auroral evening sector. By contrast, the projection indicates that the ionisation seen at the highest latitudes in the tomographic image of Fig. 1 was swept around the dawn cell, though regrettably experimental evidence in

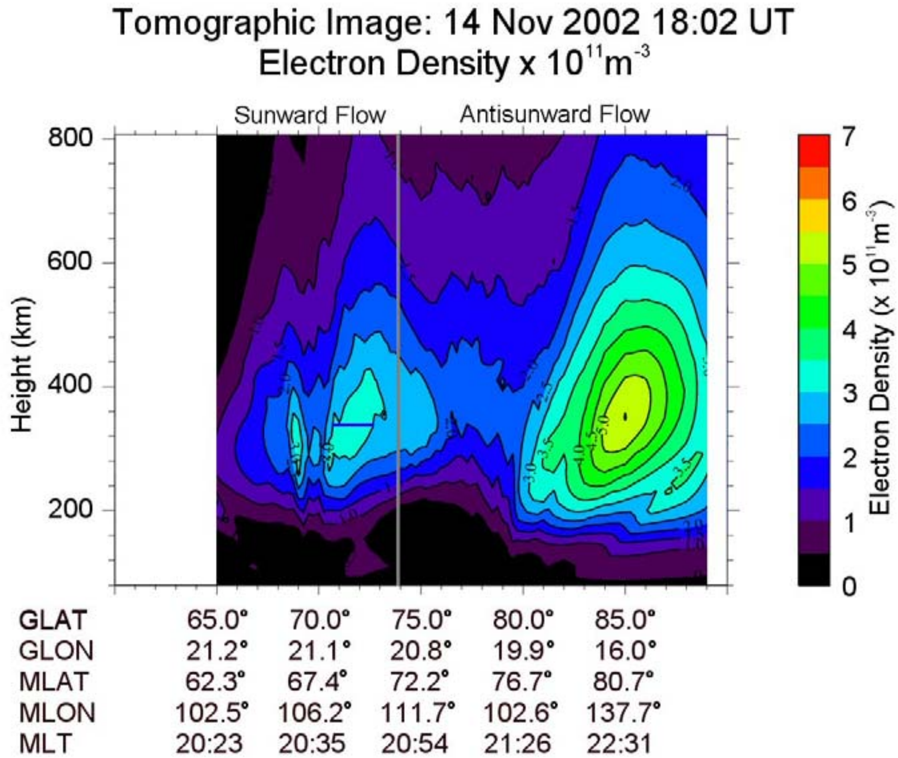

Fig. 4. Tomography image from a southbound satellite pass crossing the latitude of 75° N at 18:02 UT on 14 November 2002. The dark blue horizontal line indicates the latitudinal extent of the density enhancement of interest in sunward return flow as defined by the $3\times10^{11}\,\mathrm{m}^{-3}$ electron density contour. The vertical grey line shows the location of the flow reversal boundary between sunward and antisunward flow at 18:02 UT.

the form of another tomographic image is not available for confirmation in this case.

The expected decay of the electron densities can be estimated along the projected path. Calculations, using the recombination coefficients quoted by Brekke (1997) show that a density of $4\times10^{11}\,\mathrm{m}^{-3}$ at 350 km in cold plasma might be expected to decrease to $3.4\times10^{11}\,\mathrm{m}^{-3}$, in the absence of any production mechanism, during the time interval of 46 min between the two tomography images. The difference between the chosen level of $4\times10^{11}\,\mathrm{m}^{-3}$ in the image for the earlier time and that of $3\times10^{11}\,\mathrm{m}^{-3}$ in the second plot is thus broadly consistent with this decay, given the uncertainties in the recombination rates and the accuracy of the density estimates from the image.

The variability seen in the temporal observations made by ESR suggests that the density enhancement in the tomographic image was probably a polar-cap patch rather than a steady tongue of ionisation (TOI). The cold nature of the plasma seen at high-altitude indicates that it was likely to have originated earlier, upstream on the dayside, and was carried into the region of observation in a TOI that had been modulated into patches. A less-likely alternative interpretation might be of a uniform TOI moving spatially in-and-out of the radar field-of-view, although knowledge of the spatial and temporal structure of the convective flow on such fine scales is well beyond the capabilities of the measurement techniques available.

Rino et al. (1983) were the first to present the idea of a boundary blob in the evening auroral ionosphere. Using observations by the Chatanika radar they suggested that the structure may have been produced by precipitation of low-energy electrons from the inner edge of the central plasma sheet. EISCAT radar measurements reported by Jones et al. (1997) showed that the feature, tracked over many hours, was a field-aligned structure associated with bursts of latitudinally-localised increases in the electron temperature in the F-region, a clear indication of production in situ by soft-particle precipitation. Tomographic reconstructions of the mid-latitude ionosphere confirmed that such an enhancement formed the poleward edge of the mid-latitude trough (Kersley et al., 1997). A more recent investigation, aimed at characterising the morphology of the trough for the validation of ionospheric models, showed that a boundary blob could be identified at the poleward wall for some $\frac{2}{3}$ of the 600 troughs studied (Pryse et al., 2006). However, the production mechanism behind the formation of the blob still remains open to debate and the observations presented here provide experimental evidence for plasma reconfiguration, as opposed to impact ionisation from soft particle precipitation, thus supporting the original modelling work of Robinson et al. (1985).

In view of the conflicting evidence in the literature supporting two distinct physical mechanisms for the production of boundary blobs, it is interesting to see the presence of a narrow field-aligned enhancement at 66.5° MLAT in the tomographic image at 18:02 UT (Fig. 4). The location of this feature is equatorward of the enhanced densities that have mapped from the earlier image and interpreted as a reconfigured patch. This narrow structure has an electron density at the layer peak similar to that of the reconfigured patch, but the altitude of the peak is lower. The field alignment and lower altitude are both in keeping with production by localised soft precipitation. While impact ionisation cannot be established conclusively, it can be noted that simultaneous measurements to the south, by the EISCAT UHF radar on mainland Norway, showed evidence of localised precipitation near 18:00 UT. Hence, it seems likely that in situ soft-particle precipitation and plasma reconfiguration were both operating in the sunward return plasma flow of the evening auroral region to create a complex structure of boundary blobs that were separated in latitude. It must thus be concluded that both physical mechanisms play roles in the formation of boundary blobs. While it may be possible to attribute a single source to some of the simpler structures, in line with the evidence found in the literature, in practice, for many situations the plasma seen in the density enhancements may have had more complex origins.

It is of interest to note that there is a suggestion, in the projection of the polar patch, of higher density plasma being convected around the equatorward edge of the dawn cell. It is well established that the main ionisation trough is to be found in the post-midnight sector as well as at pre-midnight times. In the evening, it forms in the vicinity of the stagnation region between the sunward return flow and the co-rotation at lower latitudes. However, after the Harang discontinuity, the return flow at the auroral edge of the dawn cell is no longer opposed to the co-rotation. While information is now available on the statistical character and morphology of the post-midnight trough (Pryse et al., 2006), little investigation has been done on the mechanisms operating in this sector. While troughs of “fossil” ionisation from the evening may be carried round in the co-rotating flow towards dawn, the present results suggest the reconfiguration of trans-polar plasma may have a role to play in the location and details of the poleward wall of troughs to be found after midnight. Further study is clearly needed with appropriately located observations. It is known that the TOI undergoes modulation both in UT, due to the offset of the geographic and geomagnetic poles, and because of the polarity and strength of the IMF B_y component, hence leading to effects that are more pronounced in some sectors and under certain geomagnetic conditions. An early investigation, trying to compare electron densities in different longitudinal sectors using limited incoherent scatter radar data, was presented by de la Beaujardière et al. (1985). However the establishment of radio tomography chains by the International Ionospheric Tomography Community now opens up the possibility of routine comparisons of density structures in different geographic regions.

5 Conclusions

Radio tomography, EISCAT and SuperDARN observations have been used to identify a long-lived enhanced density feature in the cross-polar antisunward plasma flow. The projection of its location using the electric potential maps, from its initial observed location to a final position some 46 min later, indicates that it may have been reconfigured in the midnight sector to form a plasma enhancement extended longitudinally in the sunward return flow. Comparison of the projection with a later tomographic image at the end of the projection time interval revealed a density enhancement co-located with the projected density structure. The observations provide experimental evidence for the mechanism proposed by the modelling work of Robinson et al. (1985) for the reconfiguration of polar plasma into a longitudinally-extended feature near the equatorward boundary of the auroral oval. There is also evidence for a second plasma enhancement equatorward of the reconfigured blob, likely to have been produced by in situ precipitation. Taken collectively the observations indicate that the two mechanisms proposed previously in the literature for the production of boundary blobs are operating simultaneously to form two distinct features separated slightly in latitude.

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